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Flow and Temperature Distribution in a Naturally Stratified Thermal Storage Tank

by
Maurice W. Wildin
Chang W. Sohn

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FOREWORD

This research was performed for the U.S. Army Construction Engineering Research Laboratories (USACERL) under project 61102AT23, work unit EB-ES0, "Mass, Momentum and Energy Transport Phenomena Common to Facilities." The experiments were conducted at the University of New Mexico, Albuquerque, NM, during the summer of 1990.

The work was conducted by the Energy and Utility Systems Division (FE), of the Infrastructure Laboratory (FL), USACERL. The USACERL principal investigator was Dr. Chang Sohn. Dr. David M. Joncich is Chief of CECER-FE, and Dr. Michael J. O'Connor is Chief, CECER-FL. Dr. Maurice Wildin is a professor in the Department of Mechanical Engineering, University of New Mexico.

Appreciation is expressed to Mr. Kelly Homan, Graduate Research Assistant, University of Illinois, for his contribution to technical editing of this report.

LTC David J. Rehbein is Commander of USACERL and Dr. L.R. Shaffer is Director.

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DEFINITION OF SYMBOLS

Fr_i = Inlet densimetric Froude number

Fr_c = Critical Froude number

g = Gravitational constant

g' = Reduced gravitational acceleration, defined by $g' = g \dfrac{\Delta\rho}{\rho}$

h_c = Vertical distance between the inlet and the interface

h_i = Diffuser inlet opening height

K = A constant in Didden/Maxworthy equation

L = Distance from the diffuser to the opposite wall

Pe = Peclet number

Q = Volumetric flow rate

q = Volumetric flow rate per unit diffuser length

Re_i = Inlet Reynolds number

t = time

U,u = Horizontal component of velocity

V = Volume

α = thermal diffusivity

x = Position of the head of gravity current

ρ = Density

$\Delta\rho$ = Density difference between incoming and ambient fluids

ν = Kinematic viscosity

FLOW AND TEMPERATURE DISTRIBUTION IN A NATURALLY STRATIFIED THERMAL STORAGE TANK

1 INTRODUCTION

Background

During Fiscal Year 1990 (FY90), as part of the AT23 program, basic reseach was done on mass, momentum, and heat transfer in energy systems in Army facilities. The mechanisms responsible for creation and preservation of thermoclines in a chilled water storage system were experimentally studied at the Heat Transfer Laboratory (HTL) of the University of New Mexico.

Objectives

The objectives of this study were to investigate in greater detail the effects of mixing on the creation and maintenance of a thermocline during the charging of a thermal storage tank. The effects of inlet fluid momentum and buoyancy and temperature-induced density differences on the creation and maintenance of a thermocline were examined experimentally.

Approach

HTL had the necessary equipment to run the experiments as described in detail in Chapter 4 (Experimental Apparatus Setup). The experiments were conducted in a benchtop scale model. The variation in governing parameters (inlet Reynolds number) were realized through changes of flowrates to the inlet diffuser. The temperature distribution within the test domain were collected by a data acquisition and the collected data (flowrates, temperatures) were reduced into inlet Reynolds numbers and inlet Froude numbers to specify the conditions under which the behavior of gravity currents are to be reported.

Scope

This is an experimental study of the charging process in a naturally stratified thermal storage tank. Numerical simulation of the process is not included in the scope of this work. A comprehensive numerical simulation of a charging process based on the coupled momentum and energy equations will be examined in a future study.

Mode of Technology Transfer

Information in this report has been condensed and presented at the 1991 ASME/AIChE National Heat Transfer Conference in Minneapolis (Wildin 1991). The experimental data will help verify future numerical models for flow and temperature distributions in naturally stratified flows. Information on the degree of mixing as a function of the inlet Reynolds and Froude numbers will be used for development of diffuser design criteria for chilled water storage cooling system (an AT45 project on "Development of Advanced Cooling Systems").

2 BACKGROUND STUDIES

Thermal energy storage for building and process cooling is employed in two principal forms: sensible and latent. Each form has its advantages and disadvantages. Currently, water is the most frequently used storage medium for cooling, with the solid/liquid phase change being used for latent storage and chilled liquid water used for sensible storage.

This report deals exclusively with sensible storage in water. To reduce the cost of sensible storage tanks, both cooler and warmer water (i.e., supply and return water) may be stored in the same tank. Researchers studied ways to minimize the volume and optimize the storage capacity in the inlet side of the thermocline in a naturally stratified thermal storage tank since this mixing tends to be the dominant factor in determining the capacity of the storage tank. To minimize the volume and optimize the storage capacity, mixing and heat transfer between the warmer and cooler water must be minimized. It has been shown that the least expensive and most effective method to minimize mixing and heat transfer is to use diffusers to achieve natural stratification by taking advantage of buoyancy forces (Wildin and Truman 1985a, 1989a; Yoo et al. 1986). The effects of mixing are related to two key dimensionless parameters: the initial inlet densimetric Froude number and the inlet Reynolds number. Natural stratification involves formation of a thermocline by introduction of a fluid such as water at suitable values of these parameters (Equations 1 and 2). Of course, cooler fluid must be introduced at the bottom of the tank, and warmer fluid must enter at the top. The thermocline is essentially a one-dimensional region of large vertical temperature and density gradients between the warmer and cooler water. The thermocline moves vertically in a plug-like manner through the tank during charging and discharging.

The process of charging a stratified thermal storage tank is continuous, but it may be regarded as consisting of two principal phases. The mixing which occurs during these phases is due to somewhat different mechanisms. The first phase is at the start of charging, when fluid at a different temperature from that initially in storage first enters a tank. The ambient fluid in the tank usually is stratified in some manner, due to a preceding cycle of operation, so the temperature difference between incoming and ambient fluid may not be the maximum value specified by the design conditions. Nevertheless, a thermocline is reliably formed, or reformed, during this phase (Wildin and Truman 1985a). Mixing may be minimized by introducing the water through a diffuser such that density difference rather than inertia induces horizontal motion of the fluid across the tank (Yoo et al. 1986). This preferred type of flow is termed a gravity current. It is primarily a two-dimensional flow that forms immediately downstream of the inlet diffuser and travels horizontally across the tank at a velocity of 1 cm/s. There is negligible mixing except in and near the leading portion of the current, termed the "head," where the ambient fluid is displaced to make room for the incoming fluid. For typical stratified chilled water storage operating conditions, motion of the fluid results from the approximate 0.1 percent density difference between the entering water and the ambient water in the tank. This density difference produces a horizontal pressure difference that drives the flow. It was found that formation of a gravity current is ensured and that mixing between the incoming and ambient fluids is minimized by introducing fluid into the tank with an initial densimetric Froude number of two, or less (Yoo et al. 1986). The initial inlet densimetric Froude number is defined by:

$$Fr_i = \frac{q}{g'h_i^3} \qquad \text{[Eq 1]}$$

The densimetric Froude number is the ratio of inertia to buoyancy force. As the inertia of the incoming flow increases relative to the buoyancy force, more mixing occurs. To minimize mixing, the fluid must

be carefully introduced such that it neither has nor acquires momentum in the vertical direction toward the developing thermocline. For a bottom diffuser, for example, this means that the fluid should have no momentum in the upward direction. This may be accomplished by appropriate diffuser design and also by operation of the storage/chiller system and the distribution system such that the inlet temperature does not increase during charging, or decrease during discharging, respectively.

The second phase of the charging process occurs after the thermocline has formed and is moving upward. Most of the capacity that can be realized during discharging is stored during this phase. Because the energy that can be absorbed by cooled storage during a subsequent discharge depends directly on the outlet temperature, it is essential that the temperature of the fluid below the thermocline be as close as possible to the inlet temperature during charging. For example, an increase of 0.5 °C in the average temperature below the thermocline in a tank where the average temperature difference between tank inlet and outlet is 10 °C corresponds to a 5 percent loss of cooling capacity. This implies that mixing during this phase of charging should be minimized. The density difference between the incoming fluid and the fluid in the tank at the level of the inlet is extremely small (around 0.01 percent) during this phase so mixing occurs more readily than during thermocline formation. The dominant dimensionless parameter governing mixing during this phase of charging is thought to be the inlet Reynolds number as defined by:

$$Re_i = \frac{q}{v} \qquad \text{[Eq 2]}$$

The physical significance of the Reynolds number is the ratio of inertia to viscous force. As the inlet Reynolds number increases, the inertia of the incoming fluid increases, and greater mixing is induced both below the thermocline and in it. This results in a greater departure of the average temperature below the thermocline from the inlet temperature during charging.

Heat transfer through the thermocline is inevitable, due to the temperature gradient existing there. However, if mixing in the thermocline is negligible, which occurs at low inlet Reynolds numbers, the dominant mode of heat transfer through the thermocline is by conduction. The thermal conductivity of water is such that the thermocline thickens moderately during a typical charge, from about 1/3 m to 1 m during a 6-hour charging period, and the resultant loss of storage capacity in a diurnal cycle is not excessive. The dimensionless parameter that characterizes the increase in thermocline thickness is the Peclet number as defined by:

$$Pe = \frac{q}{\alpha} \qquad \text{[Eq 3]}$$

The physical significance of this parameter is the ratio of the rate of convection of energy into or out of the tank due to flow through it, to the rate of conduction through the thermocline. From tests on scale model tanks, it was observed that increasing the rate of flow through the tank reduced the increase in thickness of the thermocline during a charge, due to reduced time for conduction, as should be expected. It may be noted that this result occurred because there was not a compensating increase in mixing near the inlet diffuser resulting from the increased values of Fr_i and Re_i.

3 LITERATURE REVIEW

The pertinent investigations are primarily experimental. The studies reported by Lavan and Thompson (1977), Sliwinski et al. (1978), and Cole and Bellinger (1982) resulted in recognition of the importance of the inertia and buoyancy of the incoming fluid, diffusion through the thermocline (or halocline in the case of fresh water/saline water media) and geometric characteristics of the tank and the inlet/outlets. There was not complete agreement on the pertinent physical parameters or their dimensionless combinations. It was agreed that the Peclet number governed diffusion through the thermocline. To characterize the effects of mixing, Lavan and Thompson (1977) employed a Reynolds number based on inlet diameter and a Grashof number based on tank diameter. Sliwinski et al. (1978) employed an overall Richardson number using the vertical distance between the inlet and outlet as the characteristic length. Cole and Bellinger (1982) also used the overall Richardson number to explain the failure to maintain stratification in solar-heated storage tanks in systems with constant flow rate through storage. Their experiments with various configurations of inlet/outlets and internal baffles in vertical cylindrical tanks led them to a very important conclusion: that internal baffles were not promising from the standpoint of cost or performance. They also concluded that mixing was minimized in a vertical axis cylindrical tank by using disk-shaped radial diffusers at opposite ends of the tank. Thus they identified the importance of inlet configuration, and their results suggested that the dimensions of the inlet, as distinct from tank dimensions, were important.

The first investigations to focus on chilled water storage were performed in the early 1980s. They addressed the unique features of this type of storage: (1) the requirement for delivery of coolant from storage at temperatures that differ by a few degrees from the temperature of the fluid supplied to storage during charging, and (2) essentially constant tank inlet temperature during charging and discharging. Baines et al. (1982, 1983) performed tests in scale model tanks using isothermal fresh and saline water to simulate warmer and cooler water, respectively. They also briefly investigated the behavior of a vertical cylindrical tank using warm and cool water as the medium. They recognized the overriding importance of minimizing mixing near the inlet and the desirability of introducing fluid in a distributed fashion rather than through a concentrated inlet such as a pipe. They identified the appropriate independent dimensionless parameters as the Peclet number and the inlet Reynolds number (Equations 2 and 3), a densimetric Froude number (Equation 4) based on the distance from the diffuser to the opposite wall, L, and a dimensionless time, qt/L^2.

$$Fr_i = \frac{q}{\sqrt{g'L^3}} \qquad \text{[Eq 4]}$$

The importance of viscous effects was discounted, based on the assumption that the inlet Reynolds number is very large in full scale installations. It may be noted that the Reynolds number is not more than a few hundred in full scale stratified storage tanks that approach optimum performance, as discussed in the results.

Flow visualization in a rectangular tank using the shadowgraph technique revealed that an interface always developed between saline water at the bottom of the tank and fresh water in the remainder of the tank (Baines et al. 1983). It was observed that, once formed, this interface moved like a plug at a vertical speed dictated by the rate of flow into the tank, which implies no mass transfer across the interface. Results obtained from temperature measurements in a vertical axis cylindrical tank equipped with disk-shaped radial diffusers and charged with cooler water under warmer water confirmed that a thermocline formed and moved like a plug in this case, also. However, the thermocline was much thicker in this case than the interface between salt and fresh water, due to a much higher rate of diffusion of heat

than salt. They concluded that initial formation of the interface, or thermocline, could be correlated in terms of a critical densimetric Froude number as defined by:

$$Fr_i = \frac{q}{\sqrt{g'h_c^3}} \qquad \text{[Eq 5]}$$

where h_c is the vertical distance between the inlet and the interface when the interface first moves at a constant speed. It was noted that the performance of storage improved as mixing near the inlet decreased (i.e., as h_c decreased and Fr_c increased). Baines et al. (1982, 1983) demonstrated that reduced mixing was achieved in two ways: by reducing the inlet densimetric Froude number (Equation 1) and by employing a diffuser with a slot-shaped opening, rather than one with multiple circular holes. The difference between the two opening configurations was attributed to the multiple jets produced by the latter, which induced greater shear and mixing near the inlet.

It is important to recognize that the relation between Fr_c and Fr_i proposed by Baines et al. (1982) implies that h_c and, via Equation 5 the critical Froude number, depend on the inlet opening height, rather than on the distance between the inlet and outlet. Indeed, consideration of the parameters that control the mixing process near the inlet in the case of gravity current flow near the inlet reveals that the vertical distance between the inlet and outlet has no relevance as long as this distance is about ten times the thickness of the gravity current, a condition that is easily satisfied in practice.

Baines et al. (1983) identified the initial inflow to their salt-fresh water tank as a gravity current. Apparently they did not attach any special significance to this type of flow, perhaps because it was associated with mixing before an interface formed. They did emphasize the importance of introducing the fluid uniformly along the diffuser to produce two-dimensional fluid motion and thus minimize mixing.

Using warm and cool water at temperatures representative of chilled water storage, in rectangular scale model tanks equipped with linear diffusers, Wildin and Truman (1985a, 1985b) and Yoo et al. (1986) demonstrated that forming a gravity current at the start of charging or discharging is very desirable because it tends to minimize mixing during formation, or reformation, of a thermocline. A gravity current was observed to form immediately at the inlet for Fr_i of 1 or less. At higher Fr_i, the incoming flow near the bottom diffuser is a tapered wall jet with a smoother surface where ambient fluid is entrained (Valentine and Tannous 1985). The jet exists for a distance and time that depends on Fr_i. The jet-like region is terminated downstream by a density jump. Downstream of the jump a gravity current forms (Yoo et al. 1986).

Yoo et al. (1986, 1987) performed a detailed investigation of gravity current flow at the start of charging of a scale model tank with chilled water. He used an inlet diffuser that distributed the fluid as uniformly as possible across the entire width of the tank by a continuous linear slot opening. A series of experiments was performed in which water temperature distributions and fluid flow rate were measured. The flow pattern was observed by flow visualization and recorded on videotape. Tests were performed for Fr_i ranging from 0.7 to 14.5 and Re_i ranging from 44 to 65. The principal parameter varied in these tests was Fr_i. As demonstrated by the results reported here, Re_i was so small that its effects were insignificant. At low Fr_i, the gravity current formed very near the inlet immediately after more dense fluid started to enter the tank. It developed the characteristic head, and it traveled across the tank at a speed of about 1 cm/s until it reached the opposite wall and "bounced" upward. As the fluid which had risen up the wall receded, a reverse current was formed that traveled back toward the diffuser as a distinct second current, separated from the first current by a thin layer of fluid that was initially in the tank. It

was concluded that the upper portion of the thermocline initially formed during the traverse of the tank by the forward current, and that the reverse current propagated across the tank at a level near the top of the thermocline, where its density was the same as that of the water in the thermocline. The reverse current moved back toward the inlet side of the tank with decreasing speed, and its motion ceased prior to reaching that side.

Observation of the position of the head of the current at low Fr_i revealed that its motion obeyed the relation developed by Didden and Maxworthy (1982) for a constant density gravity current with a plane front as defined by:

$$x = Kt^{4/5}\left(\frac{q^3 g'}{\nu}\right)^{1/5} \qquad \text{[Eq 6]}$$

From this relation it may be deduced that the velocity of a gravity current is proportional to $q^{3/5}$, a feature whose importance will become apparent in the discussion results.

It was observed from the temperature distributions that as Fr_i decreased, the thermocline formed lower in the tank, and immediately after thermocline formation, the average temperature below the thermocline was closer to the inlet temperature. At Fr_i of 2 or less, there was no detectable difference between these temperatures (Yoo et al. 1986). This is optimal behavior and, if maintained throughout the remainder of charging, it would maximize the capacity of stratified storage. For Fr_i above 2, the temperature deviation between incoming water and water below the thermocline increased significantly with increasing Fr_i. As Fr_i increased moderately above 2, a jet formed near the inlet, but it was soon engulfed by cooler water that flooded back over the inlet. As Fr_i increased further, the jet at the inlet existed for longer times, mixing was greater as the gravity current traversed the tank, and engulfment of the jet at the inlet involved extensive mixing. Greater mixing produced a greater difference in temperature between the fluid below the thermocline and the incoming fluid as already discussed.

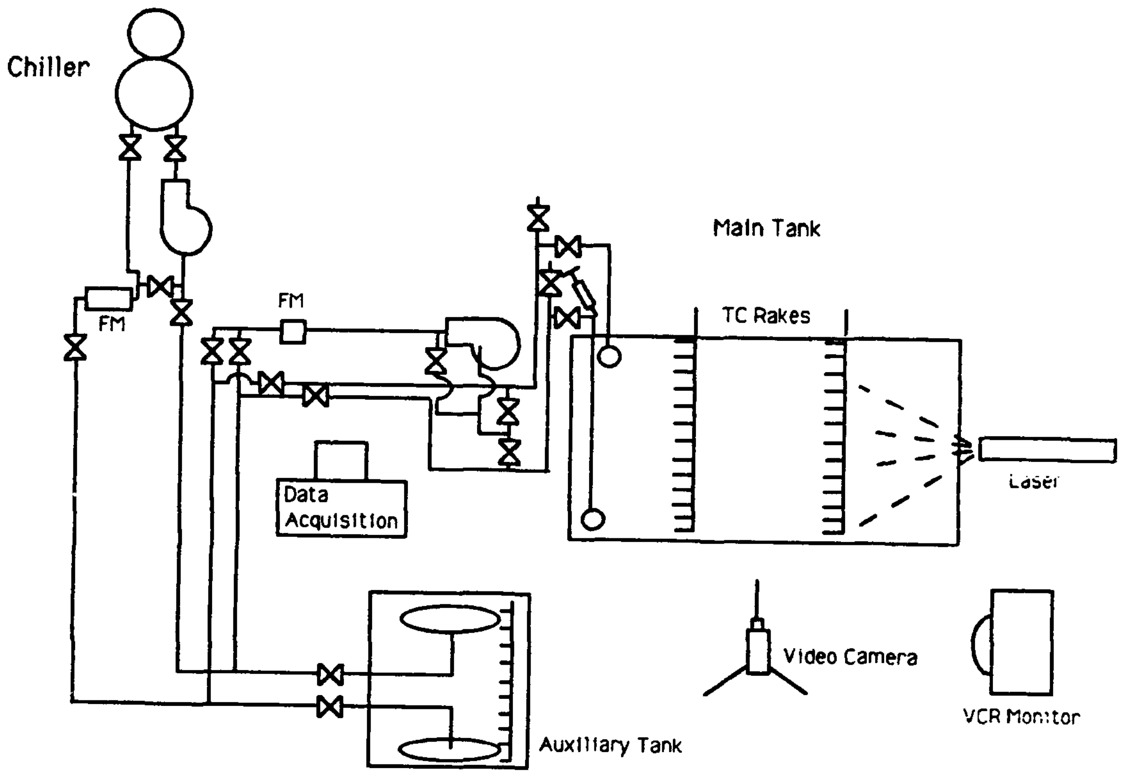
Dependence of the performance of stratified storage on the inlet Reynolds number was unequivocally demonstrated by the results of experiments performed in a 4.6 m deep, 6.1 m diameter (130 m^3, 35000 gal) vertical cylindrical concrete chilled water storage tank (Wildin 1989). Three sets of tests were performed at constant inlet temperature and flow rate with three different sets of diffusers installed in this tank. Two sets of diffusers were disk-shaped radial diffusers. One set of these disks had twice the diameter of the other. The third set of diffusers represented a second type of diffuser. It was essentially a linear diffuser arranged in an octagonal configuration to conform to the cylindrical plan view. The opening heights of the three diffusers were sized so that they all produced the same initial inlet densimetric Froude number, namely 1.26, starting with a uniform temperature tank. Due to their different total opening lengths they produced different values of Re_i, ranging from 240 for the octagon to 1700 for the smaller disk.

The data on water temperature distribution in the tank and outlet temperature during discharging demonstrated that reduction of Re_i significantly improved tank performance. The most significant result from the standpoint of storage performance was that the tank outlet temperature during discharging more closely approached the inlet temperature during charging as the inlet Reynolds number decreased. This and other features of the data demonstrated that the improved performance was due to reduced mixing during charging.

4 EXPERIMENTAL APPARATUS SETUP

System Description

The experimental apparatus employed in the tests performed during this study was constructed by modifying the apparatus developed with Electric Power Research Institute (EPRI) sponsorship and used in previous scale model tests (Wildin and Truman 1985a). The purpose of this apparatus is to supply chilled or heated water at predetermined constant values of flow rate and temperature to the test tank. The modified apparatus consists of a rectangular acrylic test tank, a steel auxiliary tank, a small water chiller, pumps, valves, and controls, and flow meters and temperature sensors as instrumentation. A schematic diagram of the modified apparatus is shown in Figure 1. The apparatus was modified by constructing a new test tank and an auxiliary tank, purchasing a new pump and a new turbine flow meter, and connecting these components with larger size piping and valves than used in the original system, to permit production of larger flow rates through the test tank. The motive for achieving larger flow rates was to perform tests for a range of the inlet Reynolds number up to values of several hundred, representative of installed systems in full scale tanks. This had not been possible with the previous system. The test tank was enlarged to more accurately simulate conditions early in the charging of a full scale tank, including reduced sidewall effects and larger distances from the diffuser to the maximum thermocline height.



FM = Flow Meter
TC = Thermocouple

Figure 1. Modified Test Apparatus.

Operation of the original test apparatus was restricted to flow rates of 6.3×10^{-5} m^3/s (1 gpm). To achieve both higher flow rates and more closely controlled test tank inlet conditions than could be achieved with continuous chiller operation during a test, an auxiliary tank that could be charged with chilled water prior to a test and then discharged at the desired flow rate through the test tank was used. A vertical-axis cylindrical steel tank, 1.5 m (5 ft) in both height and diameter and having a volume of 2.8 m^3 (735 gal), was constructed and installed (Figure 2). This tank was equipped with an access manhole and some ports on the top, to accommodate instrumentation leads and an overflow line. It was also equipped with radial disk diffusers designed to produce an inlet Froude number no greater than 2 for flow rates up to 1.26×10^{-3} m^3/s (20 gpm), to more closely approximate constant inlet temperature at the test tank.

The dimensions of the new test tank shown in Figure 3 are 0.91 m wide, 0.91 m deep, and 2.4 m long. The tank was rectangular and made of acrylic. The clear ends of the tank permitted illumination of a plane parallel to the longer side walls, and the clear side walls permitted viewing this plane. The test tank was equipped with a lower diffuser comprised of an inner circular pipe and an outer rectangular box (Figure 4). The vertical position of the diffuser relative to the floor was adjustable, to permit varying the inlet opening height. The opening height was maintained by two threaded rods inserted in tapped tabs attached to the front face. Water was supplied to the diffuser through the inner PVC plastic pipe, which had a row of drilled holes facing the adjacent tank end wall. This wall served as the back of the diffuser. Thus the water leaving the holes in the pipe turned through an angle of approximately 180 degrees before entering the tank through the slot-shaped opening between the tank floor and the bottom edge of the front face of the diffuser. Both the connections to the pipe and the holes in it were designed to distribute water uniformly across the width of the tank. The upper diffuser was a PVC plastic pipe with a row of holes in it that faced upward. The upper diffuser was less elaborate than the lower one, because it was designed solely to withdraw warm water uniformly at a low velocity across the width of the tank. It was initially

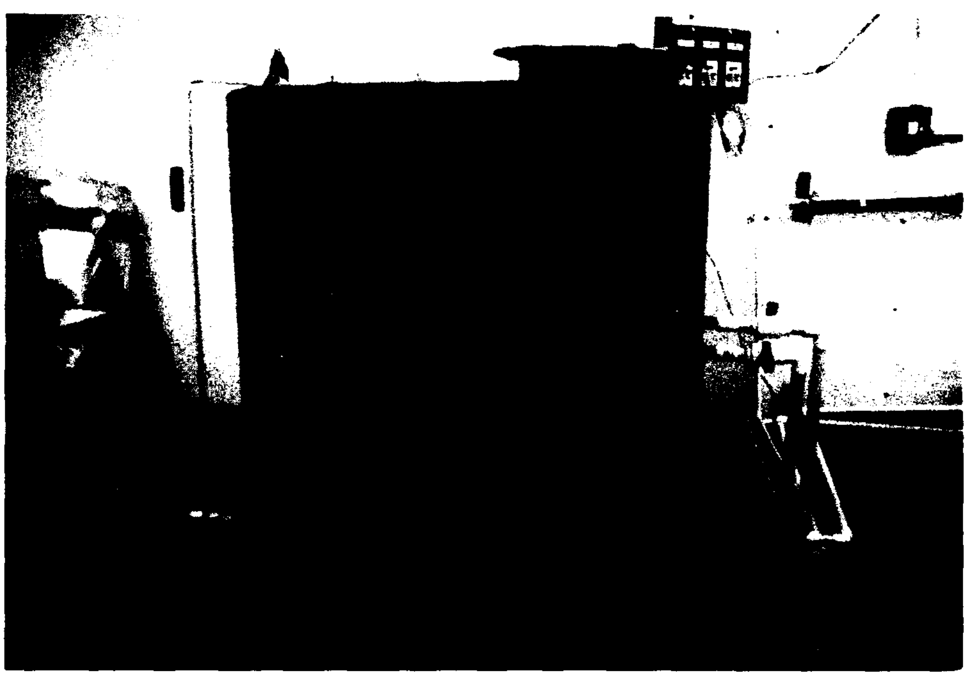


Figure 2. Steel Auxiliary Tank.

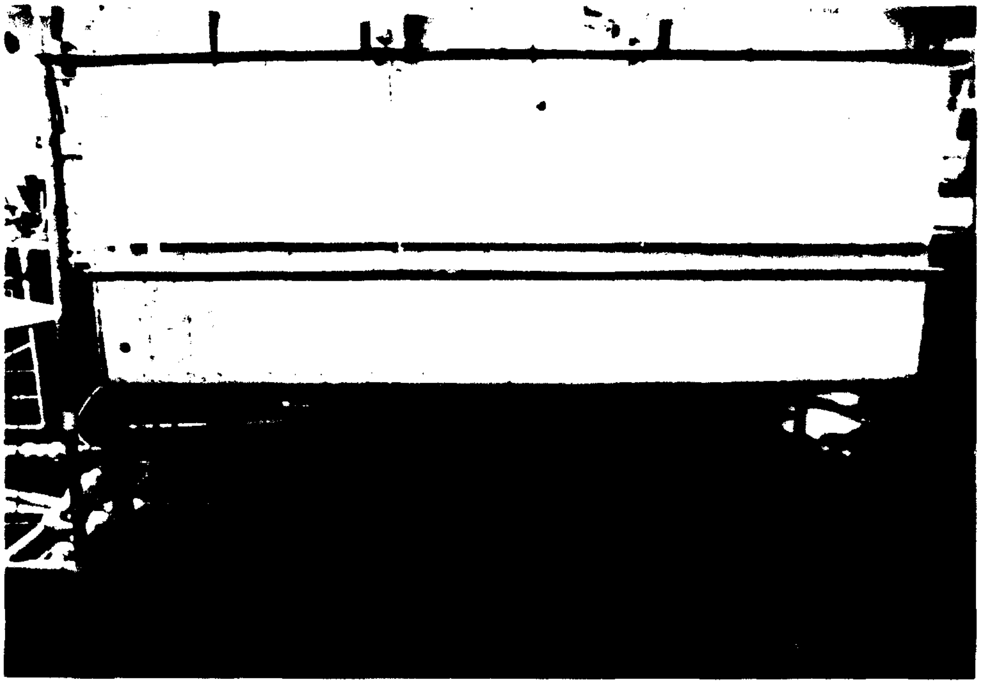


Figure 3. New Rectangular Test Tank.

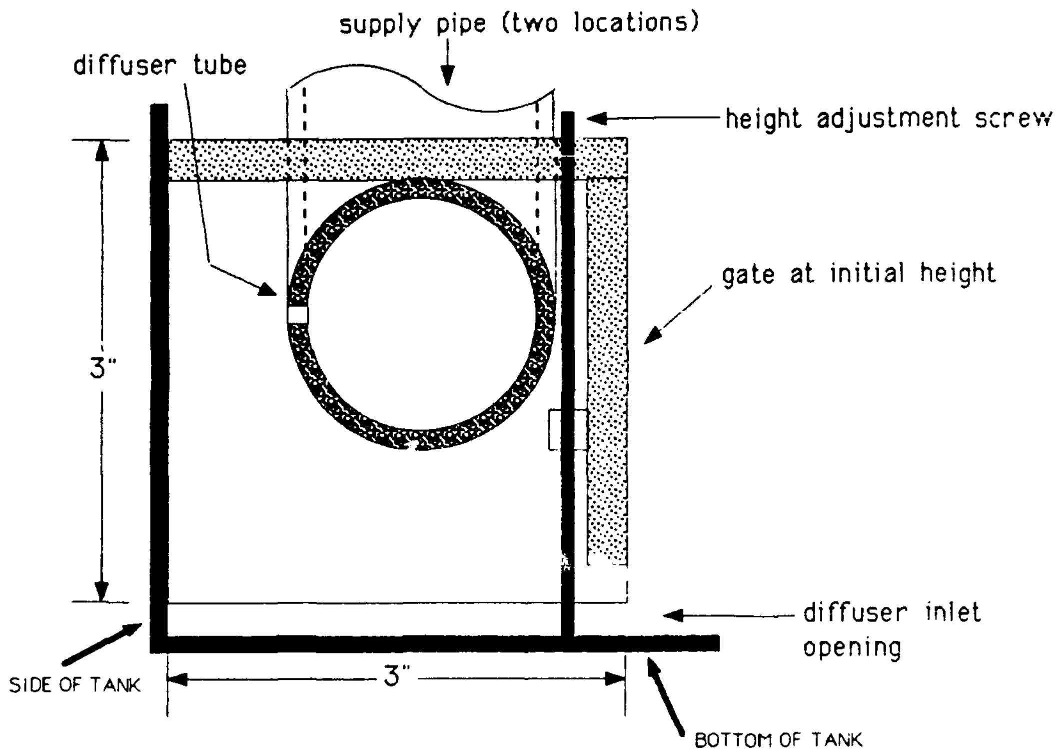


Figure 4. Lower Diffuser (End View).

located above and slightly to the right of the lower diffuser, as shown in Figure 1. Later, it was moved to the longitudinal center of the tank to reduce the outlet Reynolds number and thus the tendency to induce motion in the water above the thermocline.

To prevent excessive outward deflection of the longer acrylic walls of the test tank, two "girdles" made of 2.5 cm (1 in.) square steel tubing were fastened around the tank (Figure 3). One was located at the top of the tank, and the other was located about one-third of the height of the tank above the floor. Two brackets that engaged the outside of the top girdle were placed across the top of the tank at locations one-third and two-thirds of the distance between the end walls. These brackets served the dual functions of preventing the top girdle from deflecting significantly and supporting the two thermocouple rakes illustrated in Figure 1.

Neither the piping system nor the pump in the original apparatus had adequate capacity to produce flow rates up to the desired limit of 1.26×10^{-3} m^3/s (20 gpm). Hence a new pump and piping system was installed to connect the auxiliary tank and the test tank. Schedule 40 PVC plastic pipe with a nominal diameter of 3.2 cm (1-1/4 in.) was used in this system. The original 1.9 cm (3/4 in.) piping system was retained for charging the auxiliary tank because this pipe is adequate to handle the flow rate through the chiller. To aid in operating the test system at the start of a test, the new piping and valve system provided for circulation of water through the pipes connecting the auxiliary and test tanks, to remove air from the pipes. A bleed valve approximately 1 m (3 ft) upstream of the lower diffuser permitted precooling the test tank supply line immediately prior to initiating a test (Figure 1).

Instrumentation System

Instrumentation was used to measure the flow rate through the test tank, the temperature distributions in this tank and the auxiliary tank, and the inlet and outlet temperatures of the test tank and the auxiliary tank. The upper limit on the range of the flow meter in the original system was about 1.6×10^{-4} m^3/s (2.5 gpm), which limited the inlet Reynolds number to 225 or less. A new turbine flow meter with a range of 1.3×10^{-4} to 1.3×10^{-3} m^3/s (2 to 20 gpm) was acquired. More than 20 diameters of straight pipe upstream and 10 diameters of straight pipe downstream was installed. Two temperature rakes were constructed for use in the test tank. They each consisted of 36 copper-constantan thermocouples (30 gauge wire) spaced 2.5 cm (1 in.) apart. The thermocouple wires adjacent to the beads were oriented at an angle of 90 degrees relative to the support rod so that they extended a short distance in the horizontal direction. This was done to minimize errors due to conduction along the thermocouple wires in regions where there are strong vertical temperature gradients in the water, such as the thermocline. These rakes were located one-third and two-thirds the distance between the end walls, as noted above. The thermocouple rake in the auxiliary tank contained nine thermocouples, usually spaced 0.15 m (6 in.) apart, extending from the floor of the tank to the 1.5 m (5 ft) level. The purpose of these sensors was to monitor the temperature distribution and the inventory in the auxiliary tank, to aid in maintaining the desired test tank inlet temperature. Four temperature sensors, one in each of the inlet and outlet pipes to the test and auxiliary tanks, provided redundant measurements of these temperatures.

Dye injection ports were installed in the lines to the diffusers, as illustrated in the line to the lower diffuser in Figure 1. A hypodermic needle was inserted in a hole in the pipe, and a syringe containing the desired dye solution was attached to the needle. Thus, dye was injected into the inlet stream and was carried into the tank through the inlet diffuser. It entered the tank nearly uniformly across the entire width of the tank. It was found that the brightest and clearest flow visualization was obtained with a solution of fluorescein disodium salt, a green fluorescent dye. A solution of Rhodamine B laser dye, which fluoresces in the red, was also used for local dye injection. It fluoresced brightly only in higher concentrations, so it was not used in the main flow to the tank.

An argon ion laser was used to illuminate the tank as illustrated in Figures 1 and 5. The laser was a 7 watt continuous laser (Lexel Model 98) with its strongest emission line at a wavelength of 514 nm. A fan-shaped vertical illuminated plane was produced by placing a cylindrical rod lens with its axis horizontal in the output beam. The flow visualization results were recorded on 1/2 in. VHS magnetic tape cassettes using a Panasonic video cassette recorder and video camera. The camera displayed a time base on each frame. It viewed a long side of the tank, and it was traversed manually on a small cart, to permit viewing the illum. ated plane at a particular station along the length of the tank with minimum parallax. A grid with square elements 1 cm on a side was attached to the front wall of the tank, to aid in estimating the speed of the flow and the vertical positions of various features of the flow.

The data on temperature distributions, inlet and outlet temperatures, and flow rate were acquired, displayed online, and stored for future use by employing LabVIEW software from National Instruments Company. This software was installed on an Apple Macintosh II computer (Figure 6). Data were regularly recorded at intervals of 1 minute to 5 minutes, depending on the duration of a test. Semipermanent storage was on floppy disks.

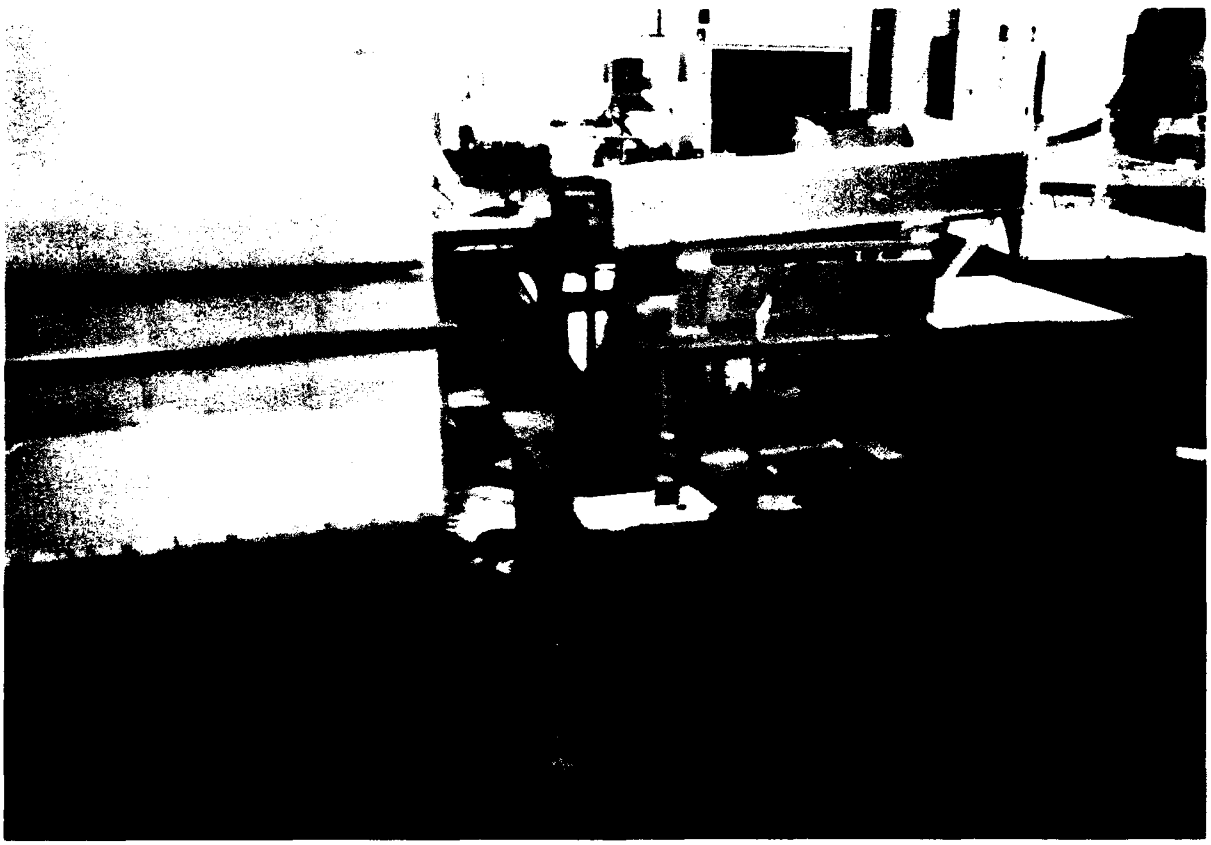


Figure 5. Argon Ion Laser.

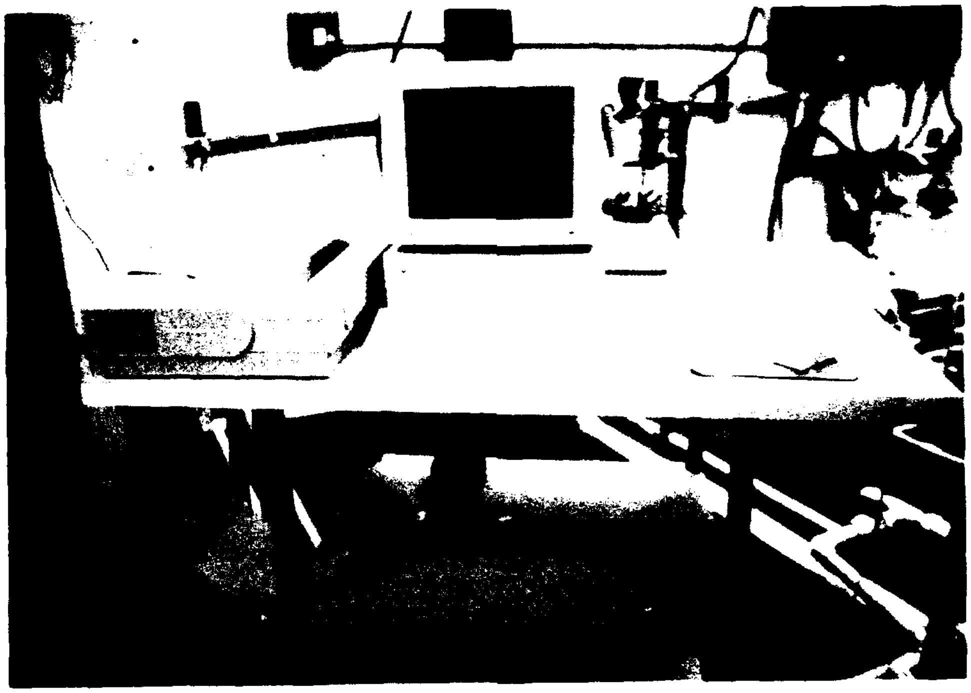


Figure 6. Macintosh Computer Displaying LabVIEW Software.

5 EXPERIMENTAL RESULTS

Experimental Conditions

Results were obtained from flow visualization and from measured water temperature distributions in the test tank for a relatively wide range of inlet conditions, including inlet Reynolds numbers ranging from 159 to 633, as indicated in Table 1. Initial inlet densimetric Froude numbers were no larger than about 2, in accord with guidelines derived from previous tests (Yoo et al. 1986). The depth of the test tank (0.86 m, 2.8 ft) permitted obtaining data after the thermocline had moved far enough above the diffuser that there was no direct interaction between the incoming flow and the thermocline. The length of the test tank is representative of the throw distance of diffusers in economical full scale installations. Judging from plan view observation of dye injected into the incoming fluid, the width of the tank (0.86 m, 2.8 ft) is adequate to negate the effects of the side walls on flow in the tank. Although the height of this tank is about one-fifth that of representative full-scale tanks incorporated in buildings, both its length and the range of possible inlet Reynolds numbers permitted obtaining results for conditions representative of full-scale tanks during the initial portion of a charge or discharge.

Experimental Results

Results obtained from flow visualization and measured data on water temperature distribution are given in Figures 7 through 16. The discussion will begin with results obtained from flow visualization, to provide an overview of flow patterns observed in the tank. These observations are consistent with and supported by the tank temperature distribution measurements, which are discussed second. Finally, a summary is presented of the implications these findings have for the design of naturally stratified thermal storage tanks.

Flow visualization showed that the flow pattern during charging of a rectangular tank with chilled water is more complex than had been recognized previously. In previous tests, only the first gravity current across the bottom of the tank and a second neutral density current immediately above it had been observed. In many tests the second current did not travel all the way back to the inlet end. The tests performed for this study revealed that two or more currents traverse the entire length of the tank,

Table 1

Summary of Test Conditions and Results for Gravity Current Speed

Test No.	Date	Inlet Reynolds Number Re_i	Initial Inlet Densimetric Froude Number Fr_i	Flow Rate (gpm)	Opening Height (in.)	Average Gravity Current Speed (cm/s)
3	7/31/90	159	0.77	2.83	0.609	1.06
9	8/8/90	191	0.42	3.44	1.000	1.27
7	8/6/90	310*	0.70*	5.53*	1.000	1.41
2	7/30/90	410	2.04	7.29	0.609	–
5	8/2/90	429	2.02	7.82	0.609	1.62
8	8/7/90	446	0.99	7.96	1.000	1.80
1	7/27/90	461	2.03	8.55	0.609	–
6	8/3/90	633	1.37	11.46	1.000	2.13

*Anticipated conditions; temperature and flow rate data were lost.

depending on the inlet Reynolds number and the height of the thermocline above the inlet diffuser. Three currents were usually observed, and at higher inlet Reynolds numbers a fourth current was noted. It is possible that additional currents occurred and were not observed, or that additional currents would have occurred if the tank had been deeper or if tests with higher inlet Reynolds numbers had been performed. At least the uppermost current was located within the thermocline. Previously, horizontal motion had been observed only below the thermocline, and the thermocline was thought to be a stagnant region (Wildin and Truman 1985a; Hussain 1989; Hussain and Wildin 1991).

As in previous tests of tanks equipped with diffusers, the initial flow to the right across the tank was in the form of a gravity current for all inlet conditions (Figure 7). This current formed soon after cooler fluid started to enter the tank, and it formed close to the lower diffuser. Both the elapsed time to formation and the distance from the diffuser increased with increasing Reynolds numbers. As a result of the passage of this current across the tank, approximately the top half of the thermocline formed, as noted by Yoo et al. (1986). The density gradient associated with the thermocline restrained vertical fluid motion of the fluid leaving the diffuser. During and immediately after the first traverse of the tank by the gravity current, a sloping interface existed between the incoming fluid and that previously in the tank. The slope angle and the initial thickness of the thermocline increased with increasing inlet Reynolds number. The second current, which moved in the reverse direction toward the inlet diffuser, formed after the gravity current reached the end of the tank opposite the diffuser. Initial formation of the reverse current involved mixing near the opposite wall, as the fluid that first encountered the wall and advanced upward receded toward the floor and started to move away from the wall (Figure 8). The reverse current was wedge-shaped as it left the wall. The wedge thickened with increasing mixing near the wall, and the extent of mixing increased with increasing inlet Reynolds numbers. At the highest inlet Reynolds number, this mixing was quite extensive, and it continued several minutes before the second current clearly formed. At lower Re_i, the reverse current typically had a smooth, symmetrical head, representative of a neutral

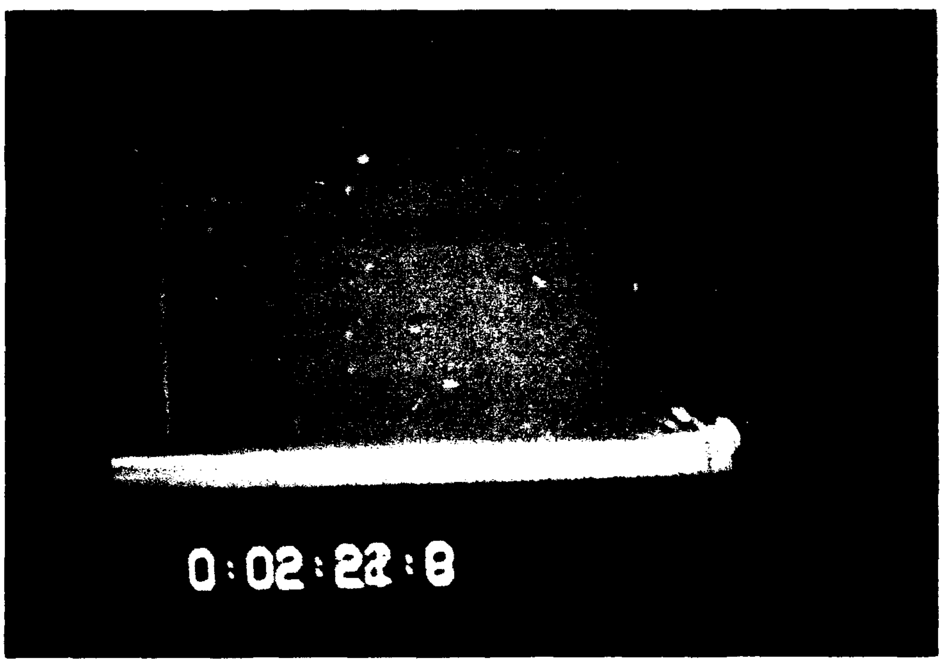


Figure 7. First Current (Gravity Current) Traversing the Tank (Inlet Re = 159 and Inlet Fr = 0.77).

Figure 8. Mixing at End Wall Opposite Diffuser During Formation of Reverse Current.

Figure 9. Head of Second Current (Reverse Current) Traversing the Tank.

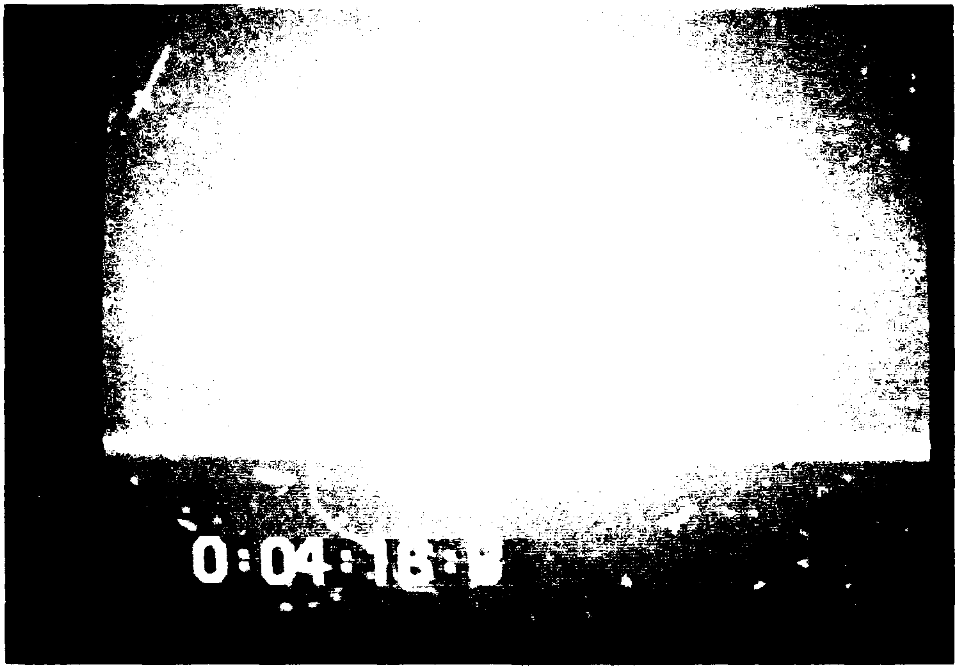


Figure 10. Vortices at Interface Between First and Second Currents.

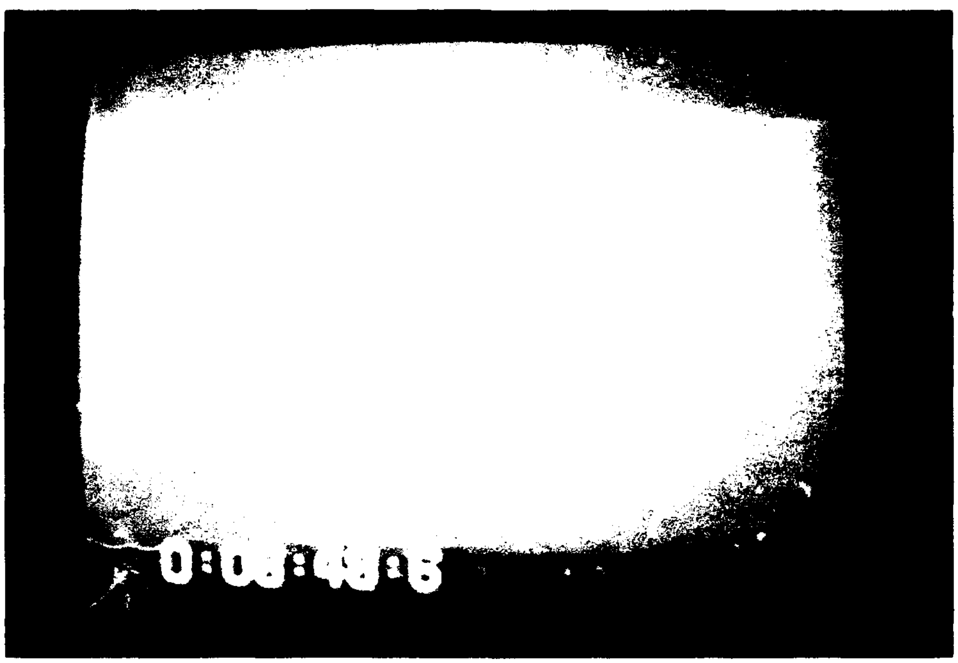


Figure 11. Velocity Profile Illustrating Existence of a Thi d Horizontal Current.

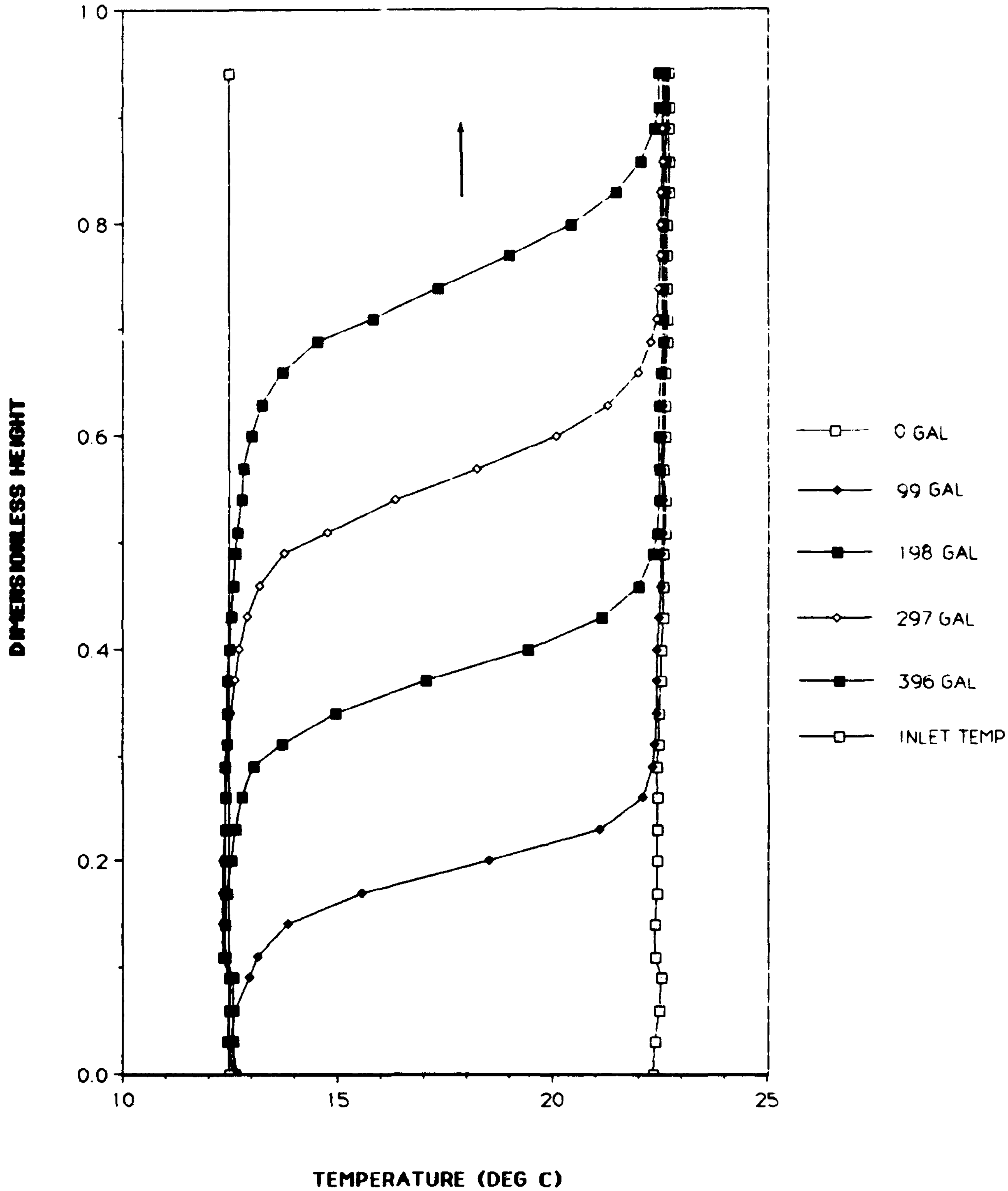


Figure 12. Temperature Distributions for Test No. 3 on 31 July 1990 (Inlet Re,i = 159, Inlet Fr,i = 0.77).

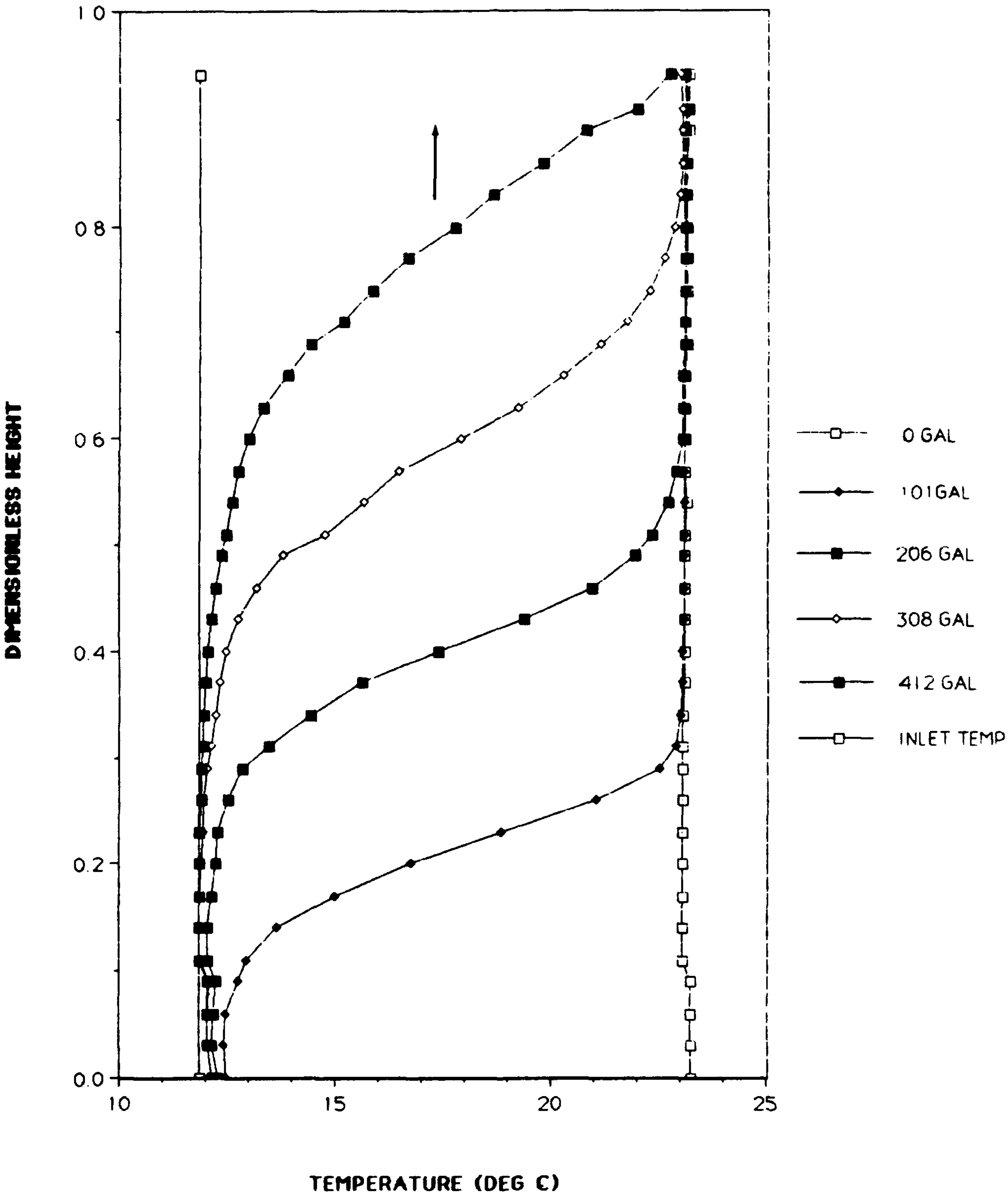


Figure 13. Temperature Distributions for Test No. 4 on 1 August 1990 (Inlet Re,i = 316, Inlet Fr,i = 1.47).

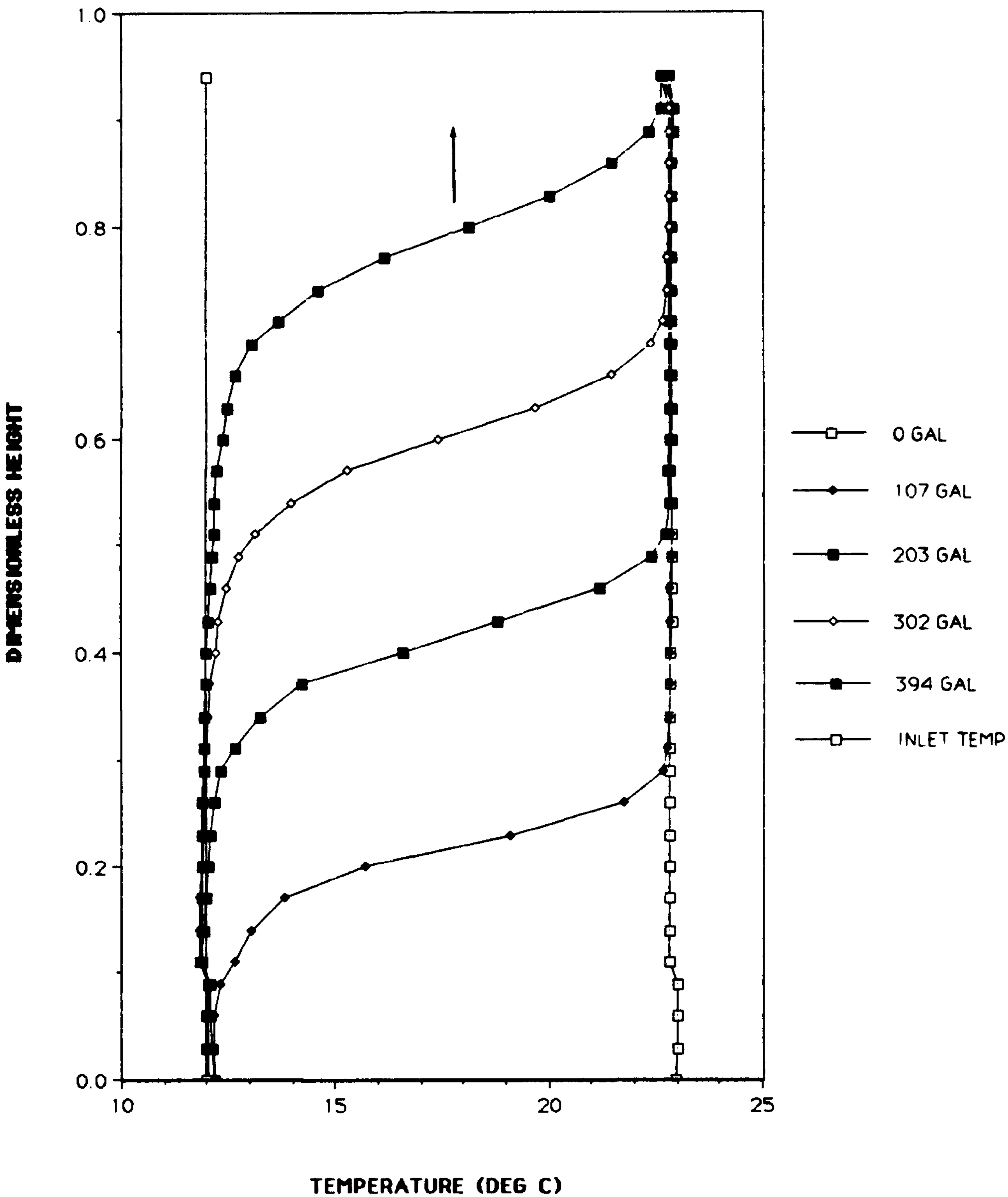


Figure 14. Temperature Distributions for Test No. 9 on 8 August 1990 (Inlet Re,i = 191, Inlet Fr,i = 0.42).

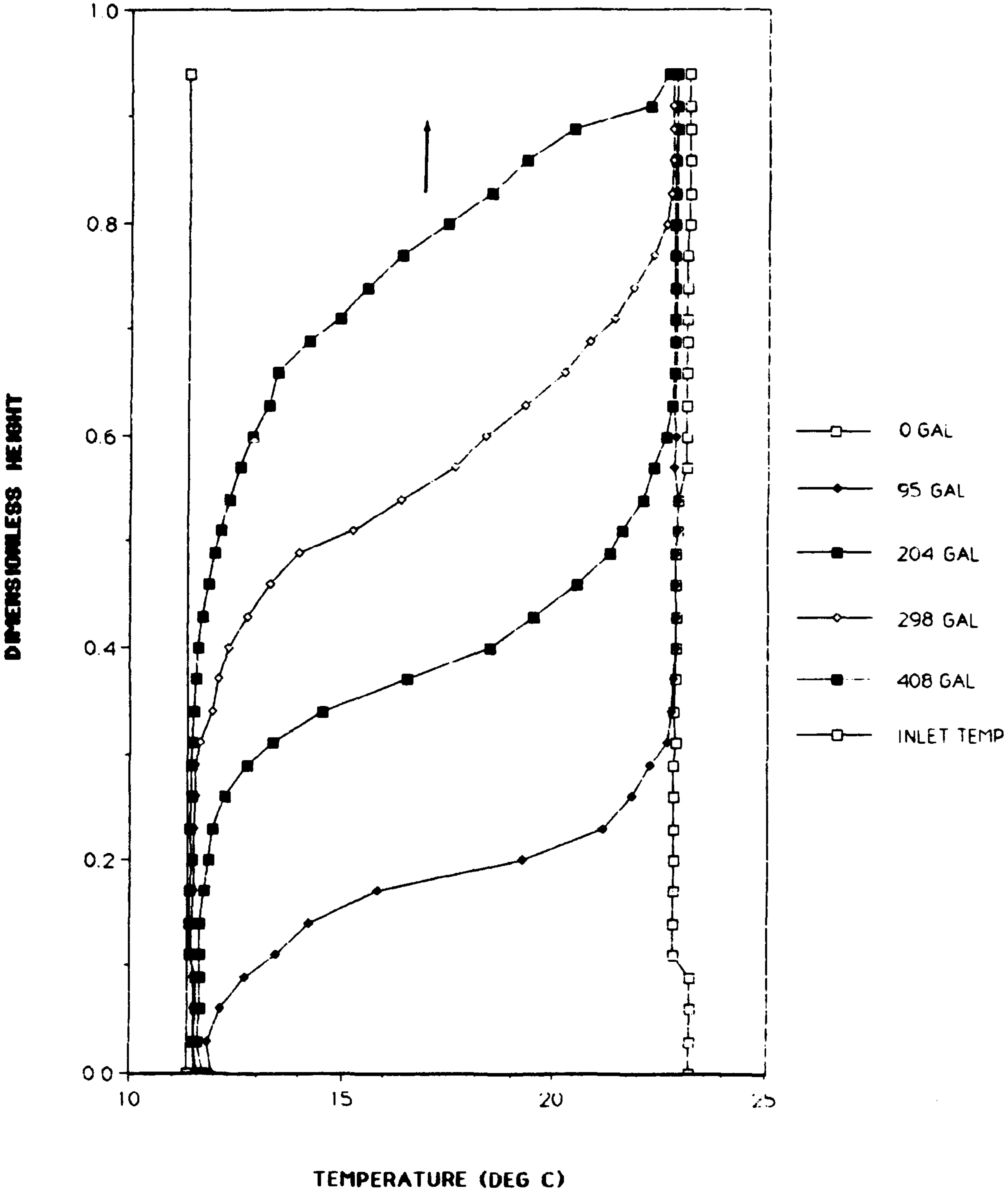


Figure 15. Temperature Distributions for Test No.5 on 5 August 1990 (Inlet Re,i = 429, Inlet Fr,i =2.02).

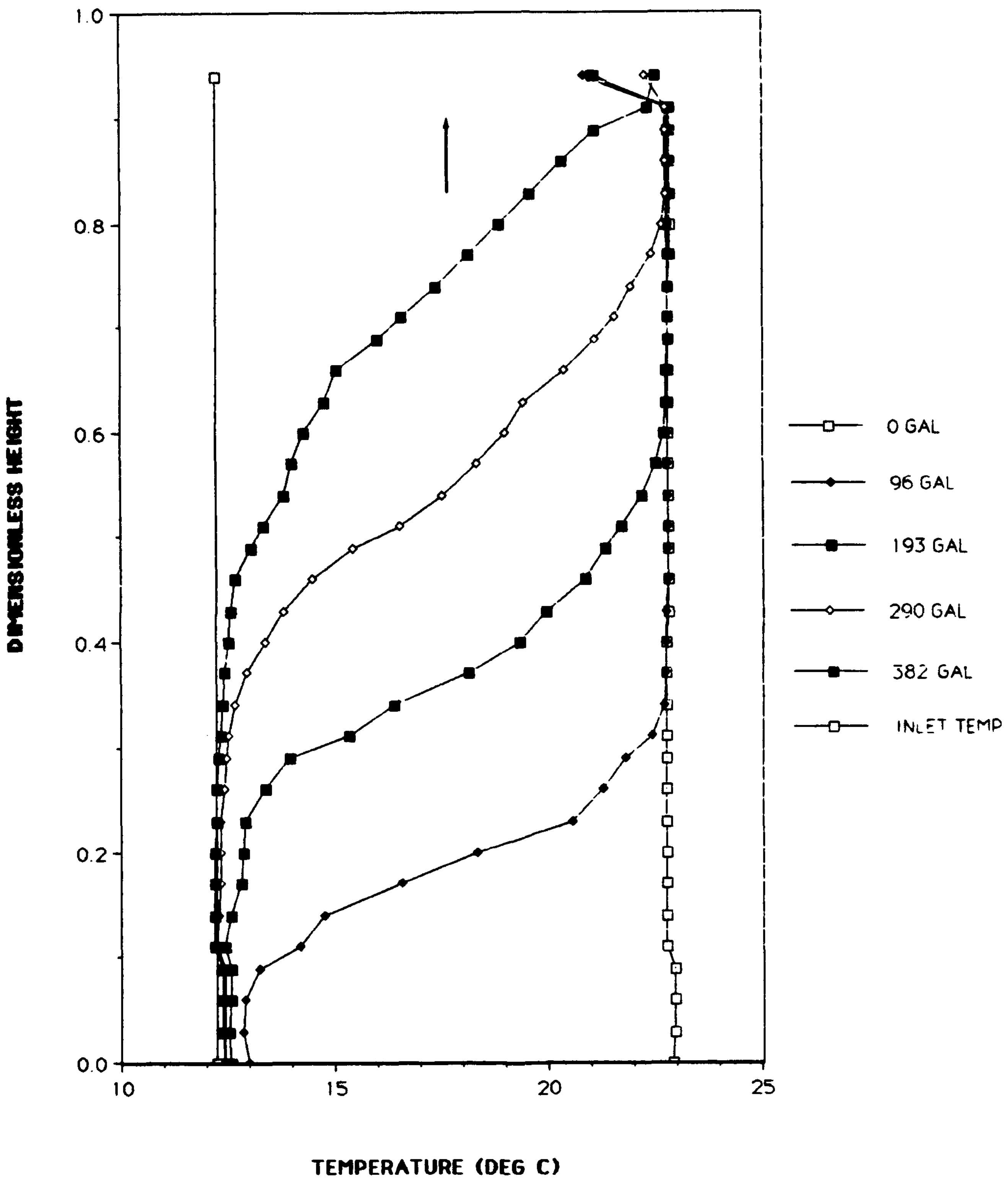


Figure 16. Temperature Distributions for Test No. 8 on 7 August 1990 (Inlet Re,i = 446, Inlet Fr,i = 0.99).

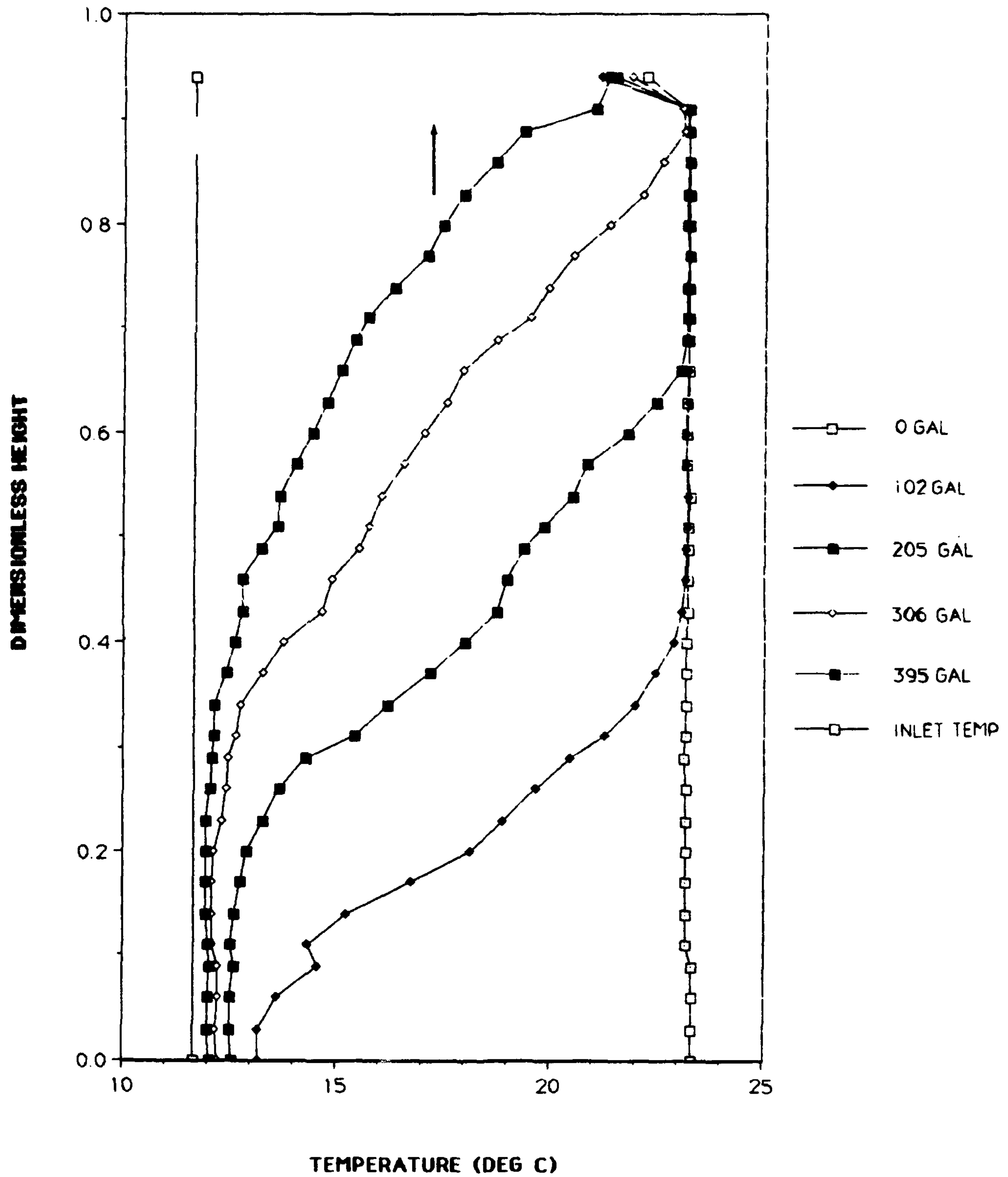


Figure 17. Temperature Distributions for Test No. 6 on 3 August 1990 (Inlet Re,i = 633, Inlet Fr,i = 1.37).

density current. The thickness of the head decreased as the reverse current traversed the tank (Figure 9). Usually, there was no evidence of vortices in the vicinity of this head, and it is believed that there was little vertical mixing between the head of the reverse current and the fluid adjacent to it. At higher Re_i, the head of the reverse current was less well-defined, and at the highest value, $Re_i = 633$, the current did not form a distinct head.

As the second current moved across the tank to the left, it ascended the sloping interface (the initial thermocline) between the first current and the ambient fluid, which was marked by a dye streak deposited during the initial traverse of the tank by the first current. At lower inlet Reynolds numbers, this interface was thin, and the second current was located at its top. At higher inlet Reynolds numbers, this interface was relatively thick, and the head of the second current was located below the dye streak, i.e., below the top of the interface. Also, at higher values of Re_i, vortices were observed between the first and second currents, at locations remote from the head (Figure 10). This is consistent with the higher relative velocity between these currents and with the lower vertical temperature gradients associated with the thicker interface. In the tests reported here, the second current consistently reached the diffuser end of the tank, whereas in previous tests the second current did not always reach the inlet end, as noted above. This is thought to be due to greater side wall effects associated with the smaller tanks used in the previous tests. It may be noted that the second current moved against the shear forces exerted on it by the fluid above and below it, in addition to overcoming gravity force in climbing the sloping interface.

The fluid above the second current moved in the direction away from the diffuser, and formed a third current. For lower values of inlet Reynolds number, the fluid motion above the second current was very slow, and it was not clear that a third current formed until the second current reached the diffuser end of the tank. At inlet Reynolds numbers of 400 or more, the third current moved vigorously soon after it formed, as illustrated by the zig-zag profile shown in Figure 11. This profile, which was visualized by injecting red dye through a portable syringe, illustrates flow to the right in the first current at the bottom of the tank, flow to the left in the second current located above first one, and flow to the right in the third current above the other two. The third current was located in the thermocline. The process by which currents other than the first two form has not been clearly visualized. At low Re_i it formed only after the second current reached the diffuser end of the tank. At Re_i of about 400 or more, it appeared to form before the second current had traversed the entire tank. Also, at higher Re_i, the third current moved rapidly at early times, but it slowed as charging progressed. However, this trend in speed was observed for all the currents.

The second unique feature of the flow visualization performed in these tests is the observation of horizontal fluid motion at the level of the thermocline. At relatively early times, this motion was associated with the third current identified above, while at later times it was associated with a fourth current, which traveled to the left. Previously, such motion had been thought to occur only below the thermocline when charging a cooled tank, as noted above. The existence of horizontal fluid motion in the thermocline had been discounted on the basis of previous observations, which were accomplished with a diffuse light source. Also, measured vertical temperature distributions had agreed well with results obtained from a finite difference model that assumed all vertical heat transfer through the thermocline is by conduction (Wildin and Truman 1985a; Truman and Wildin 1989). Nevertheless, occurrence of horizontal motion in the thermocline appears to explain some features of the temperature distributions obtained in the current tests.

It is worthwhile to note that at low inlet Reynolds numbers, 200 or less, the gravity current appeared to be very homogeneous during its passage across the tank, with no evidence of large scale motion inside it. As the inlet Reynolds number increased, there was more evidence of large scale motion in the gravity current. At the highest inlet Reynolds number, 633, this motion was quite pronounced. Also, the vortices shed from the head of the gravity current were larger and more vigorous as the inlet Reynolds number

increased. As noted above, the interaction between the first and second currents was also more vigorous at higher inlet Reynolds numbers. At the highest inlet Reynolds number, vortices were evident at the interface between these currents during the first traverse of the reverse current across the tank, as noted above.

The water temperature distributions obtained from the current tests tend to be consistent with the above description of the flow. At inlet Reynolds numbers up to at least 191, the temperature distributions were smooth throughout the charging process, and the width of the thermocline expanded minimally with time. This behavior is illustrated by the temperature distributions shown in Figures 12 and 13 for inlet Reynolds numbers of 159 and 191, respectively. The distributions are shown for various cumulative volume flows through the tank. These distributions are characteristic of the thermoclines observed during previous tests at low values of the inlet Reynolds numbers (Wildin and Truman 1985a; Yoo et al. 1986; Wildin and Truman 1989; Hussain 1989). As Re_i increased, the temperature distributions exhibited additional features of interest. The slopes of the temperature distributions shown in Figure 14 for an inlet Reynolds number of 429 decrease more rapidly with cumulative volume flow (or time) than those in Figure 13, for example, particularly at larger cumulative volume flows. (Note that the slope in this context is measured relative to the vertical axis of the plot.) If the slope change were due to conduction, an increasing flow rate or inlet Reynolds number would result in reduced slope change while the thermocline moves a given distance vertically, due to smaller elapsed time for heat conduction. Also in this case, the slope would remain smooth throughout the charging process. The fact that there is greater change in slope and that the slope is not always smooth at higher Re_i than at lower values of this parameter indicates that some other mechanism than conduction is significant. Because the observed reductions in slope are due in part to reduced temperatures in the upper portions of the thermocline, penetration of cooler water to greater heights in the thermocline could account for the observed effects. This would be consistent with a current existing at the level of the thermocline, if it is assumed that this current transports cooler water upward in the thermocline.

Decreases in slope with time (or cumulative flow) and distortion of the thermocline are also apparent in Figures 15 and 16 for inlet Reynolds numbers of 446 and 633, respectively. In fact, these features are more pronounced as Re_i increases. The temperature plots at inlet Reynolds numbers of 400 or more exhibit an indentation in the lower knee of the thermocline for a cumulative flow of about 100 gal. The indentation appears at approximately the same height in the tank where the second, or reverse, current was observed by means of flow visualization. The indentation exhibits higher temperatures than normally occur at that level in the tank. It is hypothesized that, at least for a time, the second current carries warmer water produced by mixing at the wall opposite the diffuser. It may be worthwhile noting that at higher Re_i, this mixing involved large scale counterclockwise rotation of the fluid near the wall after the second current had started to move away from the wall.

It is apparent that mixing below the thermocline increased with increasing Re_i. This is evident from the increasing difference between the tank inlet temperature and the temperature of the water below the thermocline, as illustrated in Figures 13 through 16. The water temperature near the bottom of the tank is increasingly greater than the average inlet temperature, indicated by the vertical line near the left side of each figure. (Note that a small increase in the inlet water temperature during the tests caused the average inlet temperature and the temperature at the bottom of the tank to overlap at early times for lower Re_i, and to produce the appearance of very close agreement between these temperatures at other times and at higher Re_i. Despite this artifact, a progressive shift of the temperature near the bottom of the tank above the average inlet temperature as Re_i increased is evident from these plots.) The mechanism for this mixing is not fully understood. It appears that although the currents generally tend to carry fluid upward in the tank, the extent of mixing below the thermocline increases with time due to the very small buoyancy force, associated with the progressively smaller temperature difference existing there as charging progresses. This was observed by means of dye injections later in the charging process. Although the

incoming fluid tended to remain near the bottom of the tank, it penetrated higher in the tank toward the thermocline later in the charge. The nature of the motion near the bottom of the tank was chaotic.

From the standpoint of diffuser design, the results obtained in this project are very useful. It seems clear that the inlet Reynolds number and the initial inlet densimetric Froude number are the dominant dimensionless parameters governing formation of the thermocline in chilled water storage and subsequent thickening of the thermocline and mixing on the inlet side of the thermocline. Although use of Fr_i less than about 2 ensures formation of a thermocline (Yoo et al. 1986), the tests reported here have shown that the initial thickness of the thermocline depends on Re_i, also. Furthermore, the inlet Reynolds number appears to be the dominant parameter governing flow and mixing as the thermocline moves through the tank during the remainder of charging.

6 CONCLUSIONS

Tests were performed using flow visualization and temperature measurements to obtain data at inlet Reynolds numbers from 159 to 633 and initial inlet densimetric Froude numbers from 0.42 to 2.04. Flow visualization indicates that the flow pattern in a stratified tank is more complex than previously conceived. As many as four horizontal currents have been observed, moving in alternate directions at successively higher levels in the tank. The uppermost current is usually in the thermocline.

Mixing in a naturally stratified thermal storage tank appears to depend primarily on the initial inlet densimetric Froude number, Fr_i, and the inlet Reynolds number, Re_i. Re_i is important both during formation of the thermocline and afterward. Both the initial thickness of the thermocline and the number and vigor of the currents, which affect subsequent thickening of the thermocline, increase with increasing Re_i.

At low Re_i of about 200 or less, the effects of the currents on the water temperature distribution in the tank, and therefore on the performance of the tank, appear to be minimal. The thickening of the thermocline as it traveled upward in the tank was similar to that in previous tests at low Re_i, where it was determined to be dominated by conduction heat transfer. At Re_i of about 400 or more, the effects of current flow in the thermocline on the temperature distribution in the thermocline became evident. The thermocline slope decreased more rapidly than when conduction dominated, and the slope of the temperature distribution no longer varied monotonically through the thermocline.

From the design point of view, the inlet parameters and their ranges for optimal performance of a stratified thermal storage tank have been more clearly delineated. For the tank geometry considered, the upper limit of the range of the Reynolds number for optimal stratified chilled water storage tank performance appears to be between 400 and 600. The upper limit of the range of the Froude number was determined previously, and is about 2 (Yoo et al. 1986).

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